CHAPTER V. REMOTE SENSING PRINCIPLES AND TECHNIQUES

The purpose of this chapter is to acquaint the reader with the principles and techniques of remote sensing. Sea ice studies and prediction routinely use a wider range of remote sensing techniques than any other environmental surveillance effort. The objective here is to develop a general background so that the reader understands how the various instruments function, and independent judgement is possible. In order to do this, we will examine the general principles of remote sensing: the properties of electromagnetism as it relates to remote sensing and remote sensing systems, the interaction of electromagnetic radiation with the earth's surface - particularly snow, water and ice, and finally, the characteristics and terminology of remote sensing systems. Chapter VI will describe in detail the characteristics of systems used in sea ice analysis.

Section 1. GENERAL PRINCIPLES OF REMOTE SENSING

1.1 USE OF ELECTROMAGNETIC RADIATION FOR REMOTE SENSING

Aerial photography was the earliest form of remote sensing other than the telescope. For a long time, this technique relied on the portion of electromagnetic radiation used by our eyes (the visible spectrum). Early aerial photography was usually obtained on black and white film which responded to light over a broad range of visible light. Later, it was learned that by placing a filter in front of the lens which would pass only a particular color of light, a black and white record could be made of the objects reflecting light in that range. For instance, an aerial photograph of a developed area with a red-passing filter would show bare ground and many man-made surfaces which reflect a significant amount of red light. Hence, this photograph would be useful for identifying man-made features. This technique is used by the Landsat series of satellites today.

Later, as color photography became available, color film was used in aerial photography. Again, filters could be used to enhance particular features.

1.1.1 Near Infrared Aerial Photography. During the second World War there was a need to detect camouflaged objects. Although a great deal of aerial photography was obtained, it was often difficult to detect objects which had been painted green or had been covered with cut tree branches. Some experimental film was developed which responded to to light in the near infrared portion of the spectrum, light just a little more red than the red light detected by the human eye. One of the anticipated uses for this film involved the monitoring of healthy vegetation whose chlorophyll reflects the near infrared extremely well. This film was simply a black and white film with extended sensitivity which would record the near infrared if the visible light was filtered out. Later, a color film was developed which responded to the near infrared as well as visible colors (except blue). This was called color infrared film.

1.1.2 Growth of Remote Sensing. Encouraged by these results, efforts were made to utilize other electromagnetic wavelengths such as heat infrared, microwave, and radar for remote sensing purposes. Here the topic becomes complex because the radiation does not behave exactly as light does and it is not quite as simple to understand as the near infrared.

1.1.3 Imaging Satellite Systems. Another important factor in the development of remote sensing, particularly for ice surveillance, was the development of satellite systems which routinely return images to earth. The first of these systems operated in the visible portion of the spectrum because existing television technology was most easily applied there. Quickly, however, systems were developed to make use of other portions of the electromagnetic spectrum. At this time, satellite remote sensing systems based on radar were being developed.

1.2 ACTIVE VS. PASSIVE SYSTEMS

1.2.1 Source of Electromagnetic Radiation. One of the most important distinctions among remote sensing systems involves the source of the radiation used. The easiest example to use is that of a camera. When a camera is used utilizing sunlight or even ambient light in a room, it is said to be a passive system. On the other hand, when it utilizes flash bulbs, it is an active system. That is, an active system provides its own radiation. Ordinary radar is an active system, while imaging near infrared systems are passive systems. Passive systems are used when there is sufficient illumination of the object of interest to allow detection. Active systems are used when there is insufficient radiation and it must be provided. A second reason for using passive systems is in situations where the radiation given off is not used for imaging alone, but also quantitatively describes properties of the object. Thermal infrared is an example here. The radiation measured is related to the temperature of the object.

1.2.2 Transmission through the Atmosphere. In all these systems it is necessary for the radiation to pass through the atmosphere (once for passive systems, twice for active systems). Therefore, it is sometimes necessary to keep in mind the interaction between the atmosphere and the radiation. Perhaps the best example of this is the scattering of blue light by the atmosphere. Blue light is actually scattered out of the beam from the sun. It is then scattered toward us from all directions. If blue light were not scattered, the sun would look white instead of red and the sky would be transparent. (We would see stars in the daytime; shadows would be very pronounced.) Ultraviolet light is somewhat "bluer" than blue light and it is scattered even more in the atmosphere than blue light. Furthermore, ultraviolet light will expose photographic film. On a bright day this scattered ultraviolet light will fog a photograph of distant objects. In order to avoid this, we use a filter which passes visible light but not ultraviolet light (called a UV filter). The utilization of almost every remote sensing system used requires some consideration of the transmission and scattering properties of the atmosphere for a particular wavelength. These problems will be discussed where appropriate.

1.2.3 Interaction with the Earth's Surface. A major aspect of interpretation of remotely sensed data is the nature of the interaction of radiation with the earth's surface. Each kind of surface material has its own signature. For instance, a water surface absorbs the near infrared and reflects a fair amount of green light. Snow reflects both. While it is possible for the observer to catalogue these signatures, occasionally he will encounter an object whose signature is puzzling. In those cases it may be necessary to play "detective" and consider the aspects of the surface which may be producing the signature observed. For instance, the unusual occurrence of a rainstorm upon snow-covered sea ice may create an area with unusual absorption in the near infrared. It is not likely that this signature would be listed in any reference manual.

The nature of the interaction of radiation with the earth's surface can be quite different for active and passive systems. Passive systems depend on illumination from a natural source, usually the sun or radiation emitted from the object. In this case, the angle of illumination is different from the "look" angle. However, usually there is sufficient illumination that there are few total shadows. Actually, we are quite used to this situation since we experience it daily. Most active systems depend on radiation emitted and reflected directly back to the source. This can create effects we do not experience on a daily basis. Consider how things look to you when using a flashlight on a dark night; shadows are troublesome. Yet, this is how the earth looks on airborne imaging radar.

1.3 LIMITATIONS OF REMOTE SENSING SYSTEMS

1.3.1 Scale Limitations. There can be a tremendous amount of information available to a remote sensing system. Imaging systems in particular often have more data available than they can collect and transmit back to earth or that can be processed when returned to earth. As a consequence, there are often compromises struck among data resolution, area covered, and frequency of coverage. These compromises can be a cause of some frustration to the image user.

1.3.2 Picture Element Size. There is one feature common to all imaging remote sensing systems which has a direct influence on the analysis of the imagery. This is the size of the picture element, the pixel. Perhaps the best example of pixels comes from photography. Photographic film contains many small silver halide crystals. Exposure to light causes the transparent silver halide crystals to become opaque silver crystals. The objects we see on photographic film are actually composed of many of these silver crystals. These crystals impose the limitation on the size of a clear enlargement which can be made from the film. The reason that enlargements look "grainy" is that the individual crystals on the original film are becoming separately visible. Obviously, it takes many silver crystals to define an object. For instance, a hundred crystals may be necessary just to make an object identifiable as a human being.

Satellite remote sensing systems divide the earth's surface into an array of rectangular pixels and transmit back to earth a digital signal defining the amount of electromagnetic radiation received at the satellite from that pixel. The size of the pixel on the ground defines the limiting resolution of that particular remote sensing system.

It should be clear that in order to "see" something on an image, its minimum size must be comparable to the size of the pixel. This concept will be discussed in more detail in a subsequent section.

1.3.3 Measurable Levels of Radiation. The interpretation of remotely sensed data is ultimately limited by the amount of radiation received by the recording system. Although some "image enhancement" and even pattern recognition logic can be applied, no magic is possible. This seems like an obvious statement, but very often one finds persons engaged in analysis of remotely sensed data, attempting to identify features or surface cover types when the information needed for their distinction was simply not available to be recorded. Either the reflectance or emission of the object or surface type was not distinctive compared with its surroundings or it was too subtle to be recorded. Occasionally, the analyst must ask himself if there really was a distinctive signal difference available to define the target of interest in the first place. If a negative answer is obtained, a great deal of time may be saved. Later sections will give background material upon which to make such judgements.

1.3.4 Other Limiting Factors. There are many factors which can limit the ability to receive the desired signal even if an adequate signal did originate from the earth's surface. In the case of visual signals, clouds are an obvious example. Clouds can be present over a specific study site a good deal of the time. Figures V-1 and V-2 show the average percent cloud cover over the north polar region during January and July. Examination of the January map shows that the lowest percent cloud cover (35%) is over the central arctic basin. However,

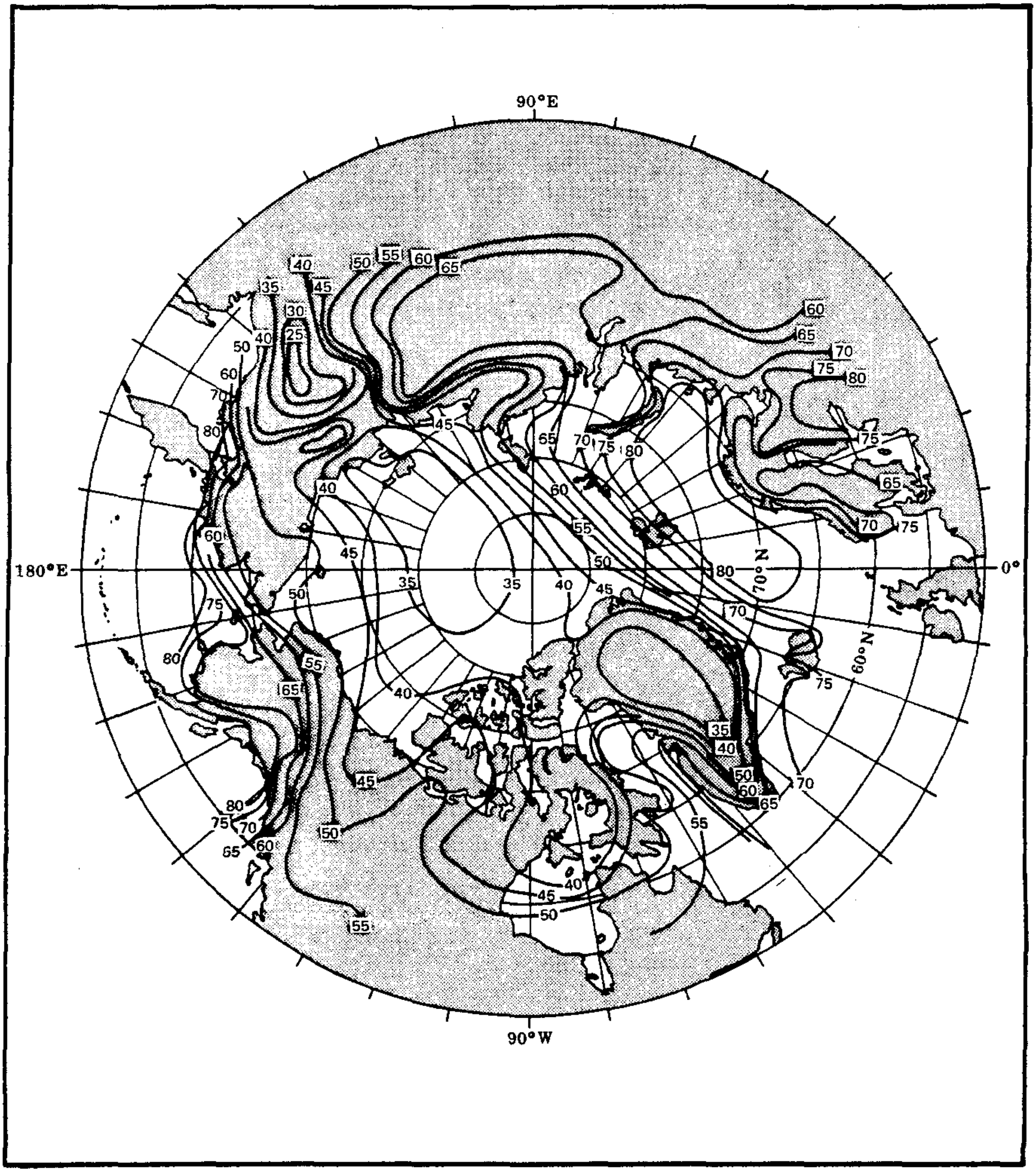

Figure V-1. Arctic Regional Cloud Cover (Percent) for January.

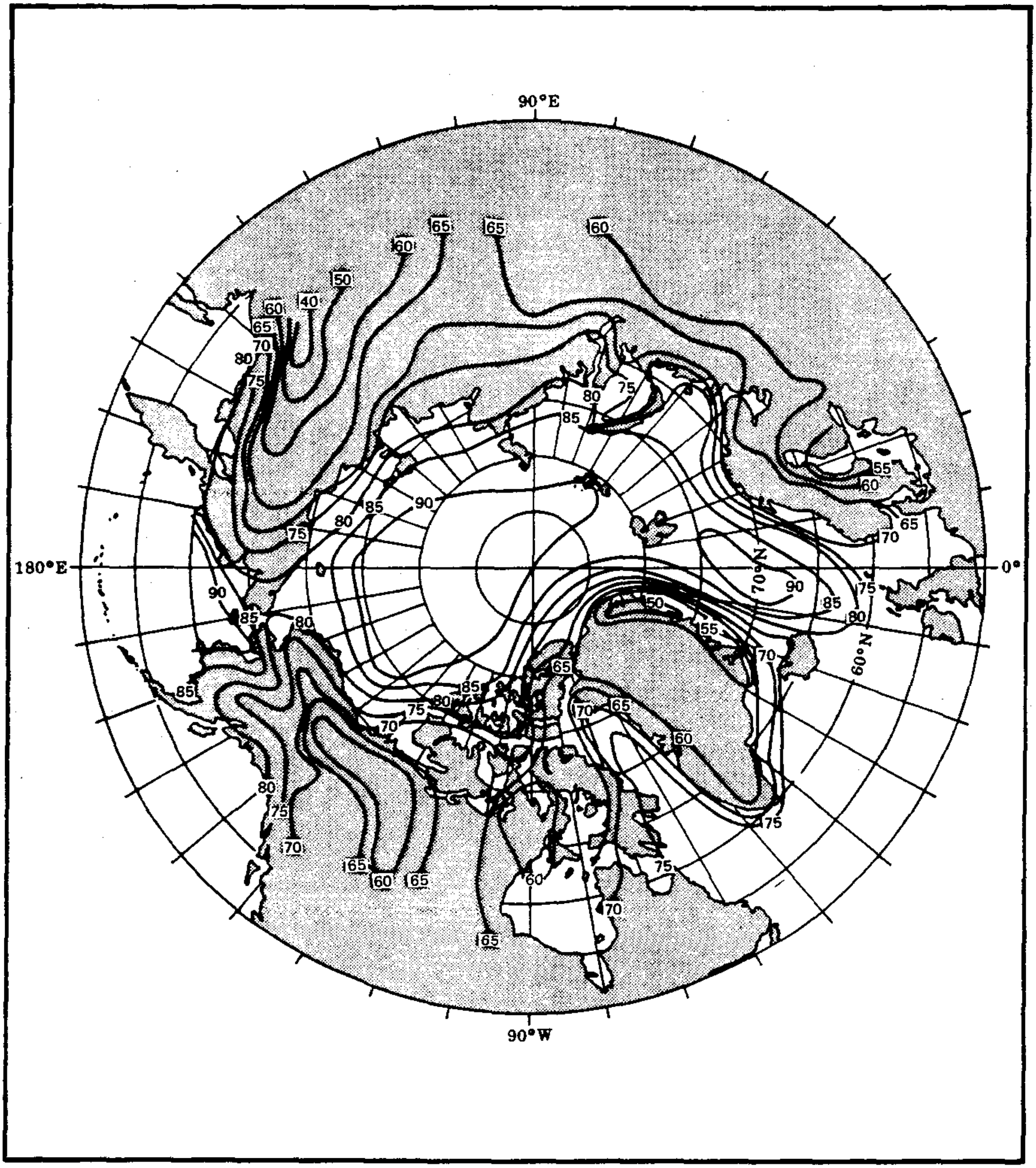

Figure V-2. Arctic Regional Cloud Cover (Percent) for July.

cloud cover over the marginal ice zones where ice edge data is particularly important at this time of year is as high as 80%. Examination of the July map shows a high percentage of cloud cover everywhere. As opposed to the January map, the highest percent cloud cover is now over the central arctic basin (90%). As a result, the cloud cover over the summertime marginal ice zone is also high.

In addition to cloudiness which totally obscures the ice, there are times when thin stratus clouds or surface fog only partly obscures satellite imagery making interpretation of ice features difficult. Many times the presence of these thin cloud forms is not noticeable until imagery is examined in detail. The result, however, is a reduced data content which may not be extremely obvious. Other remote sensing methods also have limitations that are specifically linked to each method. These limitations will be discussed in Chapter VI.

SECTION 2: ELECTROMAGNETIC RADIATION

2.1 BACKGROUND

Experiments with electricity and magnetism in the 1800's developed a body of knowledge which led James Clerk Maxwell to predict in 1886 on purely theoretical grounds that it might be possible for electric and magnetic fields to combine, forming self-sustaining waves which could travel great distances. These waves would have many of the behavior characteristics of waves on water (reflection, refraction, defraction, etc.) and would travel at the speed of light.

These properties gave rise to the possibility that light was an electromagnetic wave, but at that time, there was no proof that electromagnetic waves really existed. In 1888, Heinrich Hertz built an apparatus to send and receive Maxwell's waves. In this case the waves were around 5 meters long. The apparatus worked and, in addition, proved that the waves could be polarized which turns out to be an important property from a remote sensing point of view. After this, it was learned that light, x-rays, infrared, ultraviolet, radio, microwaves, and gamma rays were all electromagnetic waves. The only property dividing them was their wavelength ranges. The names for these divisions arise from the interaction properties each wavelength range exhibits. (For instance, we see light, radio waves are useful for communication, x-rays pass through objects, etc.)

Long before the wave description of light was developed by Maxwell, Sir Isaac Newton had also considered it and discarded the idea. The waves Newton considered were not electromagnetic, but compressional waves in the space-filling ether. Newton's reasoning was sound and based on the fact that the ether waves could not have some of the properties of light which had been observed. (Electromagnetic waves can have these properties.) Instead, he reasoned that light was composed of a vast flow of very tiny particles or corpuscles called photons. He was able to show that the flood of photons could have the known properties of light.

The discovery of electromagnetic waves created the suspicion that the photon concept was incorrect. However, in 1905, Albert Einstein was able to show that no matter how light travels from place to place, it is *emitted and absorbed in small packets of energy (photons again).* As a result, electromagnetic waves are dichotomous. They are emitted and absorbed as particles, but travel as waves. Scientific thought concerning this paradox continues to the present. Each representation has been found to have its particular utility.

2.2 CHARACTERISTICS OF THE ELECTROMAGNETIC SPECTRUM

2.2.1 Photon Description. It is useful to think of radiation in terms of photons when considering concepts like detector efficiency, the number of photons required to produce a recognizable signal. Many modern radiation detectors actually count (at ultra high speed) photons as they arrive and send these counts back to earth in digital form. These counts are useful when determining quantities such as signal-to-noise ratios. They are used to answer the question "Is a useful signal even theoretically possible from that object using this system under these circumstances?"

2.2.2 Wavelength/Frequency Relationship. We divide up the electromagnetic spectrum in terms of wavelength, although divisions based on photon energy would be equally valid. Related to wavelength is the concept of wave frequency. These quantities are related by the equation:

$$c = \lambda\nu$$

where c is the speed of light
λ is the wavelength
ν is the wave frequency

Each wavelength has a specific corresponding wave frequency and vice versa. However, because different regions of the spectrum have different applications, some regions are described in terms of wavelengths (light, for instance), while others are described in terms of frequency (radio). The accompanying figure, V-3, shows the portion of the electromagnetic spectrum commonly used for terrestrial remote sensing purposes. Note that the wavelength scale is not linear, but logarithmic. This treatment of the scale is necessary because the wavelengths range over many orders of magnitude. From a remote sensing point of view, it is usually most useful to think of electromagnetic waves in terms of their wavelength rather than their frequency. This is because some

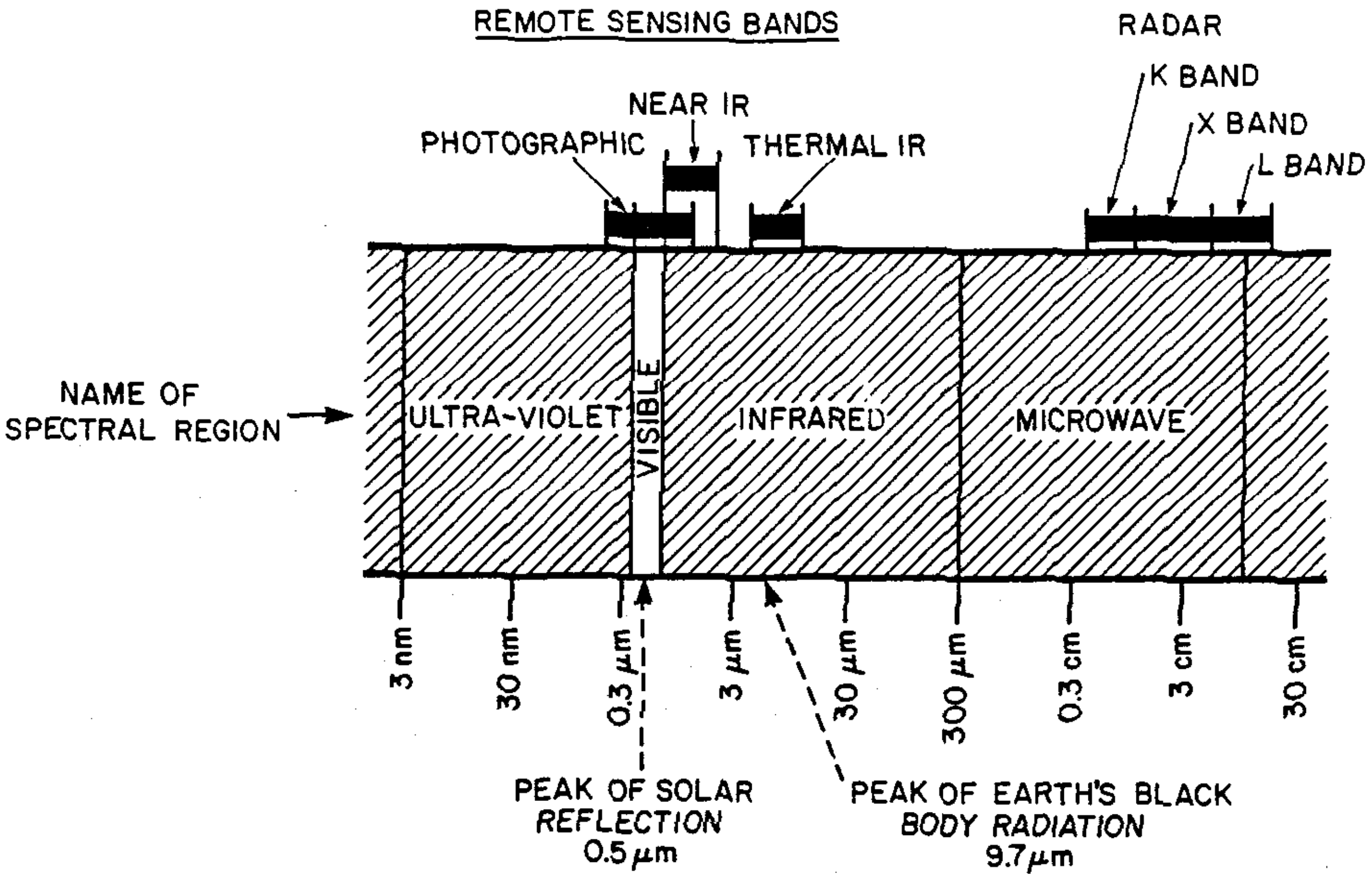

Figure V-3. Nomenclature of Remote Sensing Terms Related to the Electromagnetic Spectrum. Shown here is a map of the portion of the electromagnetic spectrum commonly used for remote sensing of sea ice. The names of the various spectral regions are associated with their wavelength range (bottom scale) while the names and ranges of the various remote sensing regions are indicated at top. Note that the wavelength scale is logarithmic. In addition, *the peaks of the solar and the earth's black body spectral radiation* curves have been indicated.

judgements concerning the interaction characteristics of radiation can be made in those terms. In general, a wave will interact strongly with objects whose physical dimensions are about one wavelength or larger. The wavelength, then, gives some hint of the sort of response to be anticipated from that spectral region.

2.2.3 Polarization. This is an important concept dealing with electromagnetic radiation. An electromagnetic wave consists of electric and magnetic fields oscillating in the plane perpendicular to the direction the wave is moving. In general, the electric and magnetic fields extend in all directions in this plane (called the wave front). However, it is possible to create waves which have their electric and magnetic fields each confined to a particular direction in the wave front. Such waves are said to be linearly polarized. The polarization is said to be in the direction of the electric field.

Radiation whose electric and magnetic fields extend equally in all directions in the plane of the wave front is said to be circularly polarized. Light emitted by an electric bulb tends to be circularly polarized.

In general, radiation is neither linearly nor circularly polarized, but elliptically polarized, where the strength of the electric field vector varies in an elliptical pattern in the plane of the wave front. The shape of the ellipse is described in terms of magnitude of the electric field strength along the major and minor axes of the ellipse. In nature, these axes are often parallel to the horizontal and the vertical directions. Hence, one speaks of the vertical and horizontal components of an electromagnetic wave. If a wave is circularly polarized, these components are equal. If a wave is linearly polarized in the horizontal direction, then the vertical component is zero. Skylight is elliptically polarized, but the relative magnitudes of the horizontal and vertical components vary in a pattern as one scans around the sun. Circularly polarized light is often changed to elliptical polarization or even linear polarization after being reflected from a surface.

Because electromagnetic radiation has this polarization property, there is actually more information contained in an emitted or reflected signal than just the total signal strength. One can measure the horizontal and vertical components of the electromagnetic signal as if they were two separate sources of information.

2.2.4 Some Characteristics of Various Portions of the Spectrum.

2.2.4.1 Ultraviolet (UV). This wavelength region has not been used to monitor sea ice and it is not likely to be used in the future. Because of the high degree of atmospheric scattering in this wavelength region, there is a tendency for imagery to appear "fuzzy". The radiation source is the sun and the systems used are, therefore, passive.

2.2.4.2 Visible Light. This wavelength region, principally the green and red portion, is used by Landsat and NOAA weather satellites to produce map-like imagery. The green portion is particularly sensitive to ice regardless of whether it is newly formed and thin or old and flooded. This portion of the spectrum is cloud-limited. As with the UV, the radiation source is the sun.

2.2.4.3. Near Infrared. This wavelength region is often detected along with visible light. Landsat and NOAA weather satellites produce images in this wavelength region. The imagery is of great utility to remote sensing of sea ice because it is highly sensitive to water/ice boundaries and water upon ice. It generally presents greater contrast between ice types and ice and water than do the visible wavelengths.

2.2.4.4. Thermal Infrared. This wavelength region is truly representative of heat. However, interpretation of thermal infrared imagery can be somewhat difficult. For many purposes, the best imagery is obtained just before dawn so that solar heating effects are at a minimum. Since the thermal infrared is absorbed by clouds and fog, it is useful to have a visual image as well as a thermal image to help identify them and the areas modified by their influences.

2.2.4.5. Microwave. Data is obtained in this region by both active and passive methods. The earth's surface does emit microwave radiation in very small amounts as a manifestation of its temperature. It is, therefore, necessary to use very sensitive microwave receivers (radiometers) to measure this radiation. This wavelength region is not affected by ordinary cloudiness, but the shorter wavelengths ($\sim$1 cm) can be absorbed by the raindrops in severe storms.

The active systems using this wavelength region come under the heading of radar. Side-scanning radar systems are operated routinely aboard Canadian ice surveillance aircraft. Imaging radar has also been used experimentally aboard spacecraft and it is likely that data from an operational satellite imaging radar system will be available relatively soon.

The active systems send out and receive back a much stronger signal than the passive microwave systems. Hence, the "background" radiation of the earth does not confuse the signal received.

2.3 SOURCES OF ELECTROMAGNETIC RADIATION

2.3.1 Black Body Radiation. All objects with a temperature above absolute zero emit electromagnetic radiation. The amount of radiation in each wavelength region depends on the temperature of the object in a complicated way but the total radiation is proportional to the object's Kelvin temperature taken to the 4th power (T^4). Hence an object at 373°K (boiling water) emits four times as much radiant energy as water at 273°K (0°C) although its absolute temperature is only 36% greater.

The exact relationship between temperature and radiated energy per wavelength for a perfect radiator is called the black body curve. Figure V-4 shows this relationship for objects at 250°, 275° and 300° K.

2.3.2 The Sun and Earth as Black Body Radiators. The sun's black body curve peaks at a wavelength of 0.5 μm or 0.0005 millimeters, the wavelength of blue-green light. Therefore, the highest radiation level available for remote sensing detectors is at this wavelength. This is also close to the center of the wavelength range of human eyesight. Hence, human eyes are adapted to making the most of the available radiant energy from the sun. However, the sun's black body curve extends from the visible wavelengths to the infrared and even to the microwave region and beyond.

The earth's absolute temperature is around 290°K (17°C). The black body curve for this temperature peaks around 9.7μm. This wavelength is well within the thermal infrared region of the spectrum. However, the earth radiates less energy at all wavelengths than the sun even at this peak for the earth's black body curve. For this reason, daytime thermal infrared measurements can be highly distorted by reflected or back-scattered solar energy.

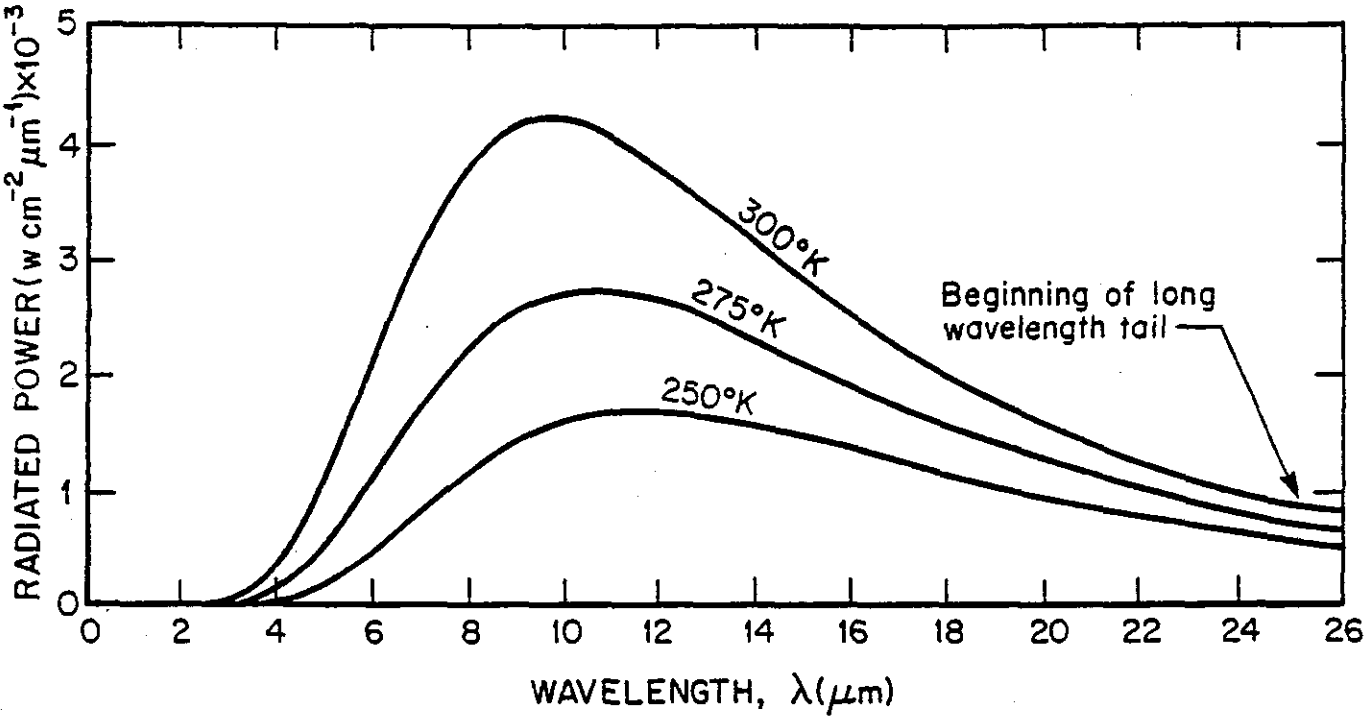

Figure V-4. Black Body Spectral Emission Curves for Temperatures in the Vicinity of the Earth's Average Temperature (290° K). Vertical scale gives radiated power in watts per square centimeter per micrometer of wavelength interval. Horizontal scale gives wavelength in micrometers.

2.3.3 Antennas. Antennas are an optional source of electromagnetic energy. This would be an active rather than passive system. However, antennas are only useful if they can produce more electromagnetic radiation in a selected wavelength band than the earth as a radiator or the earth as a reflector of solar energy. In general, this is difficult to do at visible, near infrared and thermal infrared wavelengths, simply because the earth's radiant power is so strong. (The laser provides a very useful exception to this generalization.) Once the microwave and radar wavelengths are reached, however, it is feasible to generate adequate levels of energy. In order to make the maximum use of the energy available (provided by generators aboard an aircraft or solar panels aboard a spacecraft), the energy is concentrated into a very narrow wavelength range. The narrower the wavelength range for a given amount of power, the "brighter" it will appear. (Remember, in order to be detected it must be reflected from the earth.) There are, however, practical considerations which limit the degree of wavelength concentration possible.

Engineers who build these systems speak of the antenna temperature of their antenna. This "temperature" is how hot a black body (i.e. a perfectly radiating object) would have to be in order to radiate the same energy as the antenna in the same narrow range of wavelengths at which the antenna is radiating. In order to produce radiation brighter than the sun, even in the antennas' narrow wavelength range, antenna temperature must be greater than 6000°K.

2.4 RECEIVING SYSTEMS FOR ELECTROMAGNETIC RADIATION

2.4.1 Cameras. These systems have been in use for about 150 years. The method by which data is recorded has been described in an earlier section. Here we wish to point out some general characteristics of these systems. Film can be made that is sensitive to wavelengths from the ultraviolet to the near infrared. Cameras are relatively simple data recording systems. They have several drawbacks, however: (1) The film must be developed by a chemical process before it can be viewed (2) The data cannot easily be transmitted from place to place (3) It is difficult to accurately compare the quantity of reflected light registered at the center of the image to the quantity of light registered at the film's edges.

2.4.2 Image Orthocon or Vidicon (T.V.) Cameras. These systems electronically register images. Their wavelength range largely coincides with the range of ordinary cameras. Like film cameras, the entire scene is recorded in a very brief interval. But, unlike ordinary cameras, the data can be recorded, transmitted and displayed electronically, providing a real-time capability if necessary. There are some drawbacks concerning the precision of the recorded data. These systems are in use aboard some satellites, but their use is declining.

2.4.3 Line Scanners. These systems operate over the wavelength range of cameras and orthocon and vidicon systems, and also into the thermal infrared. The method of operation is basically that of a telescope which scans the earth's surface from side to side along a path provided by an aircraft or satellite. A device sensitive to the wavelength to be monitored is placed at the focal point of the telescope. As the telescope travels from side to side, it records the amount of radiation received along a narrow line. This record is "chopped" electronically into small bits called pixels. (This term was described previously in 1.3.2 of this chapter.) An image is a mosaic of these pixels. Line scanner images have all the advantages of image orthocon or vidicon images with the added quality of precise measurement of the electromagnetic signal strength.

2.4.4 Antennas. Antennas are used in both active and passive remote sensing systems in the microwave range, and in active radar systems using wavelengths somewhat longer than the microwave range. Generally, active systems use the same antenna to receive and send the signal. Passive microwave antennas must be much more sensitive than their active system counterparts because the earth's microwave signal is much weaker than that produced by an active system. Very often these antennas are called radiometers. These systems produce an image by building up a mosaic of pixels that are similar to those produced by a line scanner. However, the scanning is performed electronically rather than by mechanical pointing.

SECTION 3. INTERACTION OF ELECTROMAGNETIC RADIATION WITH THE EARTH'S SURFACE: PARTICULARLY ICE AND SNOW

3.1 DEFINITION OF TERMS

3.1.1 Reflection. True reflection occurs when radiation which has been incident on a surface at some angle, Θ, leaves the surface at that same angle as measured from a normal to the surface.

3.1.2 Scattering occurs when light which has been incident on a surface (or within a volume such as a cloud) leaves at a wide range of angles. Very often the intensity of the scattered radiation varies with scattering angle. In some cases, such as volume scattering within our atmosphere, some wavelengths are scattered more than others. Some wavelengths will be scattered from a surface that will reflect other wavelengths. The general rule is that if the surface roughness elements are long compared to the radiation's wavelength, the radiation will be reflected; if the roughness elements are short compared to the wavelength, it will be scattered.

For instance, a side-scanning radar image of a typical ice scene will show smooth ice as almost black since nearly all the incident radiation is reflected away at the ice surface. There is often a tendency to interpret this as open water. On the other hand, even a small ridge will produce a bright return signal because the incident radiation is scattered in all directions by the many small surfaces of the ice composing the ridge.

3.1.3 Absorption. Except for unusual cases, some of an incident electromagnetic signal is absorbed by the material of the surface it strikes or the medium it passes through. In the case of both active and passive systems, absorption of the electromagnetic signal by the atmosphere plays a major role in determining which wavelengths are used. Water vapor in the atmosphere absorbs many of the microwave wavelengths leaving a few "windows" through which we can transmit and receive this information.

Water strongly absorbs radiation in the near infrared portion of the spectrum used by Landsat band 7 images and NOAA series spacecraft (near IR band images). This absorption is so strong that wet snow and ice can be interpreted as water unless data from other wavelengths are available. Microwave radiation is also strongly absorbed by a thin film of water.

3.2 EMISSION OF ELECTROMAGNETIC RADIATION BY THE EARTH'S SURFACE

3.2.1 Emissivity. We have already discussed the "black body" curve relating wavelength and intensity of radiation at each wavelength. The total energy radiated by a perfect radiator is:

$$I_P = \sigma T^4$$

where I_P = the total radiation emitted by a perfect radiator

σ = an empirical constant determined by experiment (known as sigma)

T^4 = absolute or Kelvin temp. raised to the 4th power.

Very few objects are perfect radiators (i.e. black bodies) but their total radiated energy can be related to a black body by a simple constant, ε, called the emissivity.

$$I_R = \varepsilon I_P$$

where I_R = is the actual radiated energy

ε = a constant between 1 and 0 (1 being the emissivity of a perfect radiator)

3.2.2 Brightness Temperature. In terms of total radiated energy it is possible to define an effective temperature, T_B, as the temperature required of a (perfect) black body to radiate as much energy as the nonperfect radiator at temperature T. (Clearly, T_B will be less than T.)

To do this, we relate the energy radiated, I_R, to its effective temperature, T_B, as if the radiating source were a perfect black body:

$$I_R = \sigma\ T_B^4$$

However, we must understand that T_B is not the source's true temperature, T, but merely its effective temperature.

From above, we have the relationship between I_R and T:

$$I_R = \varepsilon I_P$$

but $I_P = \sigma T^4$ so $I_R = \varepsilon(\sigma T^4)$

and since $I_R = \sigma T_B^4$

we have $I_R = \sigma T_B^4 = \varepsilon(\sigma T^4)$ and $T_B^4 = \varepsilon T^4$

or $T_B = \varepsilon^{\frac{1}{4}} T$

We now have the relationship between an object's true temperature, T, and its effective temperature, T_B. The constant of proportionality is the object's emissivity taken to the 1/4th power.

3.2.3 An Example: Thermal Infrared Temperature Measurement. As an example, if we were to find the effective temperature of a surface with $\varepsilon = .5$ at an actual temperature of 270°K, we would have:

$$T_B = (0.5)^{\frac{1}{4}} \times 270° = 0.84 \times 270° = 227°$$

Thermal infrared scanners are calibrated to give true temperatures of perfect radiators. Thus, if a thermal scanner were aimed at the surface in the example above, it would yield a temperature of 227° although the temperature of the surface was actually 270°. The only way we can get the true temperature of the surface would be by knowing its emissivity and by rewriting the above second equation to yield T:

$$T = \frac{T_B}{\varepsilon^{\frac{1}{4}}} \text{ or } \frac{227°}{0.84} = 270°$$

In other words, thermal IR temperatures are obtained by dividing the temperature recorded by the instrument (i.e. the effective temperature) by the emissivity taken to the 1/4th power.

One may wonder why the effective temperature of a material with an emissivity of 0.5 is only 43° cooler than its actual temperature. The reason is that the emissivity relates total energy radiated, but this quantity is proportional to the 4th power of the temperature. Thus, the equivalent of a large change in emissivity can be accomplished by a small change in effective temperature.

So far we have considered the total energy radiated by an emitting body. However, this does not necessarily relate directly to temperature measurement. The measurement of temperature is one of the most difficult measurements to perform accurately, particularly by remote sensing methods. A great number of methods are used, each with its own characteristic problems, attributes, and particular range of applicability. Here we are only concerned with the measurement of the temperatures of water, ice, and snow over a temperature range from a few degrees above 270°K to about 250°K. There are two principal wavelength regions used: the thermal infrared and the microwave. Because these two methods are essentially quite different, they will be discussed separately.

3.2.4 Thermal Infrared. The methods for sea ice analysis used in this wavelength region measure true temperature to differentiate between ice and water. The instruments used are not much different from those of a line scanner measuring visible light. The thermal scanner accepts a broad range of wavelengths covering the main portion of the black body curve for radiators whose temperatures are in the vicinity of 270° K. The amount of energy in this portion of the black body curve contains most of the total energy radiated and, is, therefore, proportional to T_B^4.

Thus, as discussed previously, small changes of temperature are easily detected because they cause large changes in the energy radiated. Furthermore, the emissivities of water and ice are almost equal (at ε = 0.96), eliminating ambiguities arising from differing emissivities. For example, the 5% temperature change from water at 273°K to ice at 260°K will cause a measured energy change of 21%.

In addition, small changes in emissivity are unimportant since the T^4 influence on energy radiated is much greater. This is convenient because snow has a somewhat lower emissivity (around 0.95). Thus, snow upon the ice surface will lower the energy radiated by only 1% and, therefore, not result in an incredibly low temperature measurement.

The relative independence of water, snow, and ice temperature measurement from the value of emissivity is considered to be an attribute allowing unambiguous differentiation between ice and water. However, it can also be a liability when the ice and water are both close to the freezing point, for then they radiate very nearly the same energy and it is difficult to distinguish between them (see Figure IX-12).

3.2.5 Microwave. As mentioned previously, the methods used in the microwave wavelength region are essentially radio techniques, while thermal IR techniques are basically optical in nature. Besides this difference, there are two fundamental differences between the detection of ice types by these two methods: the relative emissivities are very important in this wavelength region and the energy radiated is directly proportional to the temperature. This sounds like a contradiction compared to the thermal infrared where radiated power is proportional to T^4, but the explanation is reasonably simple. The microwave radiation measured is far into the long-wavelength tail of the black body curve (See Figure V-4). In this wavelength region the energy radiated is approximated by the Raleigh-Jeans equation where it is equal to the emissivity times the first power of the temperature, or simply εT. Hence, in the microwave region it is correct to relate actual temperature (T), brightness temperature (T_B), and emissivity, ε, in the following way:

$$T_B = \varepsilon T$$

However, several factors must be kept in mind. First, although we are detecting water and ice at temperatures around 273°, we are measuring the energy radiated at wavelengths far from the peak of radiated energy. And, although at the peak energy portion of the radiated energy curve the energy radiated is nearly proportional to T^4, at the long-wavelength tail of the curve it is more nearly proportional to T. (Overall, the total energy radiated is precisely proportional to T^4.)

Secondly, ε is wavelength dependent. Here again, because most of the radiated power is concentrated near the peak of the radiant energy curve, ε near these wavelengths becomes the overall emissivity for thermal IR measurement and ε values for long wavelengths where little energy is radiated, can be ignored. However, the emissivities of long wavelengths cannot be ignored when measurements are actually made in this wavelength region. In the 1.5 cm microwave region, water has an emissivity around 0.50 while first-year ice has an emissivity around 0.92. Furthermore, multiyear ice has an emissivity of 0.84 yielding the possibility of making a distinction between these ice types. Finally, snow is essentially transparent at this wavelength which is extremely useful for ice surveys.

3.2.6 Identification of Ice Types on Microwave Imagery. In this wavelength region, both temperature and emissivity are important. Suppose in the 1.5 cm region we have an image containing water at 273° and first-year ice at 250°, the effective temperature of each will be:

$$T_{B\ water} = 0.5 \times 273° = 136°\ K$$

$$T_{B\ ice} = 0.92 \times 250° = 230°\ K$$

Because of its much greater emissivity, the ice actually emits more energy than the water, although it is colder.

Thus, in a region where there is only water and first-year ice (for instance, many areas around Antarctica), the ratio of water and ice is roughly the fractional position of the temperature measured between 136° K and 230° K, or:

$$R = \frac{T_B - 136°}{230° - 136°}$$

where T_B is the measured effective temperature.

If $T_B = 136°$, R = 0 (no ice).

If $T_B = 230°$, R = 1 (all ice).

However, the real world is not quite so simple. First, in regions where there is only first-year ice, surface conditions such as wetness can drastically alter the measured effective temperature of the ice, reducing the concentration of ice given by the above ratio. Second, in regions where there is multiyear ice, the ratio can also be lowered in areas with lower emissivity.

The second problem can be eliminated by adding a second microwave channel operating at a different wavelength. The emissivities of first and multiyear ice and water are strongly wavelength dependent. By monitoring emitted radiation on a second channel, entirely new data can be obtained. This data and that obtained on the first microwave channel can be combined in a pair of simultaneous equations to yield the true ice concentration. (Assuming the first problem, wetness, does not exist.)

Wetness can, in principle, be accounted for by adding either a third microwave channel or true surface temperatures as obtained from thermal infrared sensors.

Clearly, the ice analyst cannot solve simultaneous equations on a pixel by pixel basis. This is the sort of problem best performed by a computer. The precise formula the computer uses in making these calculations is called an algorithm. Usually the formulation of the algorithm used to treat ice data is not available to the ice analyst. For instance, the Nimbus Scanning Multichannel Microwave Radiometer (SMMR) data is treated by a computer at the Fleet Numerical Oceanography Center in California and transmitted to the ice analyst. It is important for the ice analyst to know that the SMMR data is being treated by a computer using a man-made algorithm which is not infallible.

3.3 SPECIFIC CHARACTERISTICS OF THE INTERACTION OF ELECTROMAGNETIC RADIATION WITH SNOW, ICE, AND WATER

This section catalogs the interaction of electromagnetic radiation with materials of interest to the sea ice analyst. The order of presentation starts with visible wavelengths and progresses through longer wavelengths.

3.3.1 Visible Light Wavelengths:

3.3.1.1 Green Light (Landsat band 4 and AVHRR visible band).

Snow: High albedo. Light scatters well in all directions regardless of wetness of snow.

Water: Low albedo in deep, clear water. Albedo increases with decreasing water depth from around 10 meters. Suspended sediment greatly increases albedo.

Ice: High albedo relative to red and near IR wavelengths for all ice thicknesses, but varies from low for light nilas to high for first-year gray-white. Highly responsive to thin ice forms. Tends not to differentiate among thicker forms.

3.3.1.2 Red Light (Landsat band 5 and AVHRR visible band).

Snow: High albedo. Light scatters well in all directions. Wet conditions decrease albedo somewhat.

Water: Low albedo in relatively deep and clear water. (Not influenced quite as much as green light by shallow depth or suspended sediment.)

Ice: Albedo varies from low for gray ice to high for thin, first-year (lower than green light). Moderately responsive to thin ice forms. Thickness differentiation continues to thin first-year stages. Will not repond to thinnest ice forms.

3.3.2 Near IR Wavelengths (Landsat bands 6, 7 and AVHRR near IR).

Snow: High albedo. With dry snow, light is scattered well in all directions. Wet snow conditions drastically reduce albedo.

Water: Low albedo. Not further influenced by water depth over 30 cm. Only responds to very high sediment loads.

Ice: Albedo ranges from low for gray ice to high for first-year ice.

3.3.3 Thermal IR (AVHRR thermal band). Snow, ice, and water all have nearly the same emissivity (ε = .95). Ice and water surfaces are identified in terms of their actual temperature.

3.3.4 Microwave Emissivities of Water, First-Year and Multiyear Ice. In general the emissivity, ε, of various materials is not constant but varies with the frequency of the emitted radiation. Furthermore, the emissivity is different for the two polarization components of radiation, and these emissivities both change with viewing angle. Figure V-5 shows the variation of emissivity with microwave frequency for calm sea water, first-year ice and multiyear ice for both horizontal and vertical polarization components at a 50° nadir viewing angle. (Note: the SMMR microwave radiometers obtain data at this viewing angle.)

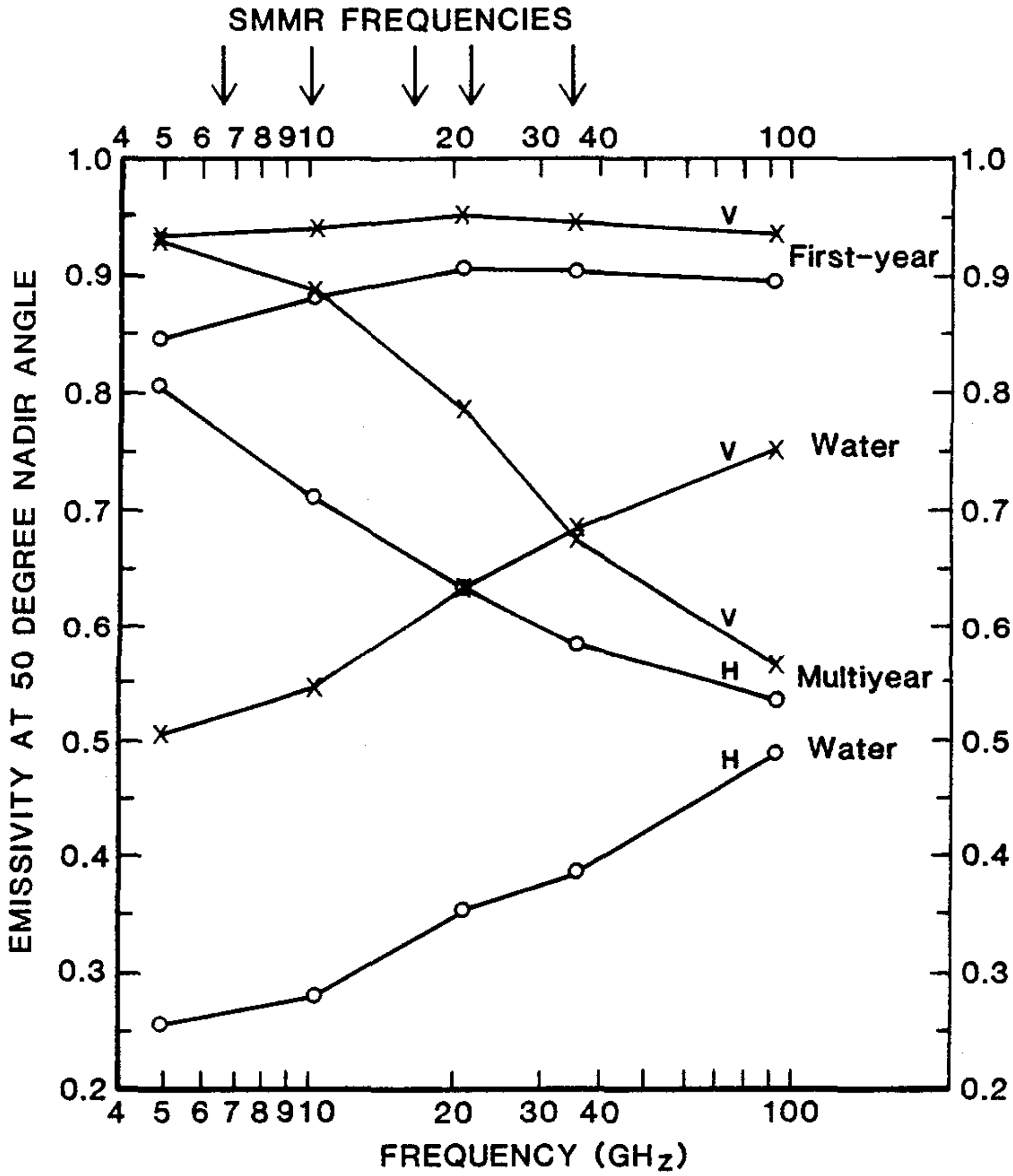

Figure V-5. Variation of microwave emissivities of calm sea water, first-year ice, and multiyear ice. Frequency for horizontal and vertical polarizations at constant 50° viewing angle (as measured from nadir). The five frequencies of the Scanning Multichannel Microwave Radiometer (see Chapter VI, Section 4) are indicated at the top. (Svendsen, el. al., 1983).

SECTION 4. CHARACTERISTICS AND TERMINOLOGY OF REMOTE SENSING SYSTEMS

This section discusses various characteristics of remote sensing systems in general and introduces the terminology used to describe those characteristics.

4.1 *DATA ACQUISITION AND GENERATION OF DATA PRODUCTS*

We are now ready to discuss in more detail some aspects of data acquisition and the generation of data products which have a bearing on data interpretation.

4.1.1 Orbital Characteristics. There are two basic satellite orbit types used to monitor large portions of the earth's surface. These are the geostationary orbit and the polar orbit. We will discuss the simpler of the two first.

4.1.1.1 Geostationary Orbit. *In order for a satellite to* attain a desired orbit, it must move at a specific speed. For satellites just above the earth's atmosphere (around 500 mi) this speed is about 17,000 mph. At this speed a satellite orbits the earth in about one and a half hours. As higher orbits are attained (and the satellite is further removed from the earth's gravitational field), the speed required is reduced. At a distance of approximately 23,500 mi, the speed required is 6,150 mph. At this rate the satellite circumnavigates the planet in 24 hours. *If the satellite is directly above the equator and traveling in* the same direction as the earth is turning (i.e. eastward), it will remain above a particular point on the equator. This is called a geostationary orbit because, with respect to the earth, the satellite is stationary.

A remote sensing system placed aboard a geostationary satellite has the ability to continuously monitor a particular location on the earth's surface, or a whole hemisphere. The GOES (Geostationary Operational Environmental Satellite) is a well known operational geostationary satellite. Images from this satellite are obtained every thirty minutes to give weather forecasters a hemisphere-wide view of changes in cloud patterns.

Unfortunately, the ice-covered regions of the world cannot be seen very well on this imagery because they are viewed at an oblique angle. Its greatest value to the ice analyst comes from the ability to detect ice in the Great Lakes.

4.1.1.2 Polar Orbit. Most of the satellites currently in orbit are in polar orbits. Most of these satellites are at altitudes between 500 mi and 1000 mi and, as described above, require approximately one and a half hours to complete an orbit. However, a wide variety of additional orbital characteristics can be chosen to further define the motion of a satellite. For instance, the locations of successive orbits as projected on the earth's surface can be a very important factor. This characteristic can be adjusted to yield a wide variety of satellite coverage frequencies and repeat patterns. However, some desired factors are obtained at the expense of others, principally the maximum latitude of the satellite's orbit as projected on the earth. Landsat, for instance, does not cover farther north than 80°N, but its frequency of coverage has many characteristics which are desirable to the users of its data.

A point to remember here is that very few polar orbits actually cross the poles.

4.1.2 Picture Element. Most satellite remote sensing systems in current use utilize radio transmission to transmit image information back to earth. The image to be transmitted is divided into small rectangular cells called picture elements (pixels). On the earth, the image is reconstituted by reassembling these pixels into the same array in which they were recorded.

4.1.3 Gray Level. The information recorded for each pixel represents the amount of radiation measured from that area on the earth's surface. In other words, the radiation is averaged over the pixel. When the pixels are reassembled to form the image for viewing, each pixel is given a uniform level of gray or gray level representing the amount of radiation which has been measured from that corresponding area. This process limits the amount of information on a satellite image. If such an image is sufficiently enlarged, the earth's surface appears to be nothing more than an array of rectangles with varying levels of gray.

Gray level can also be used when referring to an object on a satellite image. (First-year ice has a higher gray level than open water on a near IR positive image.) However, the gray levels as seen on an image can be manipulated and care must often be taken to understand what has been done in this regard in order to accurately interpret an image.

4.1.4 Gray Scale. The image interpreter must be aware that the gray levels of pixels as displayed on an image may have been purposely rearranged in some systematic manner from those recorded in order to enhance interpretation. The guide to understanding the system of gray levels as assigned is to examine the image's gray scale. The gray scale of a satellite image is the relationship between the radiation measured at the satellite and the corresponding gray level assigned to pixels. Very often the gray scale appears as a bar broken into bands, each with a particular shade of gray. Corresponding notations describe the relationship between these bands and the radiation level they represent. For instance, the gray scale can be reversed, making white things black and vice versa. (This is called a negative image.) Or certain gray levels can be assigned a new gray level not assigned to any other feature. (For example, thermal IR images are often given gray scales which make ocean temperatures around freezing either very black or white so that the region where freezing is taking place can be identified easily and quickly.)

4.2 FACTORS RELATED TO DATA INTERPRETATION

This section discusses basic satellite parameters which have a significant bearing on satellite image interpretation. These factors are present to one degree or another in all satellite remote sensing systems.

4.2.1 Detectability, Resolution, and Discrimination. These three factors are often mistakenly lumped together under the term resolution. However, each has its own specific definition and use.

4.2.1.1 Resolution. This term has a strict meaning referring to the ability to identify separate objects. When a system is referred to as having a resolution of x meters, it means that the objects must have a physical separation of at least that distance to be identified as separate objects. On satellite images this distance is obviously related to the pixel size as represented on the earth (pixel footprint). For instance, the pixels representing two bright objects must have one darker pixel between them in order for the viewer to suspect that two separate objects are being represented. For this reason, the pixel footprint size is generally referred to as a particular detector's resolution. As a practical example, the footprint of AVHRR visual channel is approximately 1.1 km. In general, two objects must be separated by that much distance to be distinguishable.

4.2.1.2 Detectability. In some respects this is a more useful, yet complicated term. Even though a single object might be smaller than the pixel footprint or resolution, it may be detected. For instance consider a single narrow lead 1/4 the width of a pixel running across a satellite image. Although the lead is smaller than a pixel, there is sufficient contrast between the black water and the white ice in those pixels containing the lead that they will appear darker than the pixels representing the surrounding ice. Thus, the lead will be detected. Yet, since its size is less than the resolution, it is not be possible to determine whether it is a narrow open lead or a wider lead frozen to some intermediate stage between the water and surrounding ice. In general, highly contrasted objects may be detected when they are smaller than the resolution distance.

4.2.1.3 Discrimination. This term refers to the ability to determine in terms of grey level whether two classes of objects are present (for instance, gray and gray-white ice). Ultimately, discrimination depends on the distinction possible between the gray levels as recorded by the satellite and presented on the image. It may be that there is not sufficient data recorded for two ice types to be represented by two different gray levels. Or the individual steps on the gray scale used to produce a particular image were too close (in terms of shades of gray) for such a distinction to be made. Finally, the physical arrangement of the two ice types (relatively small intermixed floes for instance) may make such a distinction impossible.

4.2.2 Signal Averaging Over Pixels. This subject has been mentioned in the previous discussion in terms of detection of objects smaller than the remote sensing system's resolution. In that case, signal-averaging over pixels allowed the detection of a lead too small to be resolved.

However, this detection was obtained at the expense of an ambiguity concerning the thickness of ice in the lead. This relatively common ambiguity can become a serious problem if the area contained by a pixel contains several ice types or ice with a range of surface conditions. Such averaging presents problems on microwave and thermal IR imagery at the ice/water boundary. The microwave case can become particularly troublesome because the pixel footprint size is very large and often contains many ice conditions. A resulting inaccurate analysis can involve errors whose size ranges over tens of miles. Improved data analysis techniques involving several wavelengths will help to reduce these errors.

4.2.3 Registration of Satellite Data to Maps. The construction of a useful product from remotely sensed data generally depends on the fitting of the data to maps of the earth's surface. This creates problems arising from several factors:

4.2.3.1 Problems Arising from Geometry. It is difficult for remote sensing systems to take into account the viewing angle between the satellite and various points on the earth's curved surface. In general, this problem increases with the field of view of the particular imaging system because more curvature must be taken into account. A computer program may be utilized to perform this function, but it should be kept in mind by the image analyst that this transformation is not always particularly accurate and errors can result.

4.2.3.2 Problems Arising from Pixel Array Warping. Once pixel data are received on earth, the satellite image is compiled using a fixed rectangular grid of pixel locations. This method assumes that the pixel information (i.e. radiation intensity level) was recorded on a corresponding grid aboard the satellite. This requires that the satellite does not roll or pitch while the pixels are being measured and that the measuring system (often a mechanical device) operates very smoothly. This is not completely possible. As a result, data is occasionally assigned to a image pixel that was recorded from the area on the earth assigned to a neighboring pixel. This effect causes a general warping of an image involving distances of up to a few pixels. Accurate correction procedures involve precise knowledge of exactly where a few particular pixels should appear and a subsequent computer-driven unwarping of the data. This is a complex process and is not done on a routine basis. In practice, the effect is most important near land or shoals. In these cases the imagery is manually registered to these points of interest, leaving increasing errors with distance from shore.

4.2.3.3 Registration to a Particular Map Projection. It is impossible to completely and accurately represent the earth's curved surface on a flat sheet of paper. A large variety of techniques are used to project points on the earth's surface to produce a flat map, each with its own particular utility (preserving angles, preserving uniform distances, etc.). Remotely sensed data is obtained in its own particular projection, depending on the mechanics of how that particular system works. In many cases, the imagery is provided to the ice analyst in that same projection unless it has been transformed by a computer into some other map projection. If accurate mapping is desired, the projections of the data provided and the map to be produced must be taken into account.

4.3 INTERPRETATION AMBIGUITIES

The analysis of remotely sensed sea ice imagery requires constant vigilance to avoid errors arising from ambiguities in interpretation. These ambiguities develop because it is impossible for the remote sensing system to gather complete information concerning the ice. The following sections list some of the more common problems of this type.

4.3.1 Pixel Averaging Ambiguities. These interpretive problems arise because the gray level assigned to each pixel represents an average of the light measured from that pixel's representative portion of the earth's surface. Thus, for example, a pixel containing a thin lead between two floes will appear darker than surrounding pixels representing only floe surfaces. However, this pixel could have just as well contained a wider lead that had frozen over but was still not as white as the surrounding floes. Unless other data is available, such as a second data channel operating at another wavelength, this lack of precision regarding the lead simply remains.

4.3.2 Unanticipated Surface Conditions. Most remote sensing signatures are based on an assumption that some anticipated surface conditions exist. However, this may not be the case. For instance, on visual wavelength imagery, a recent snow would make many thin ice categories appear identical to thick first-year and multiyear ice. Similarly, a wet surface can make ice appear as ocean on some passive microwave imagery. Such wetness could result from sea state as well as melting.

4.3.3 Incorrect Assumptions Regarding Anticipated Response. Each remote sensing system is based on the physics of a particular portion of the electromagnetic spectrum. However, it is possible for the ice analyst to begin to think in terms of a system responding to particular surface features consistently and anticipate that the same surface feature will always yield the same response. Thus, while thermal imagery actually records the temperature of the earth's surface as modified by its emissivity, there may be a tendency to think that it records the presence or absence of ice. However, when ice is melting, its temperature is very close to that of the surrounding water and it can be invisible on thermal imagery.